

FABRICATION OF TUNABLE QUANTUM WELL INFRARED PHOTODETECTORS (QWIP), POLARIZATION SENSITIVE QWIPs AND ENHANCED COUPLING GRATING STRUCTURES

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Final Report

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1.0 Introduction

This project was initiated in April 2001 to investigate the properties of intersubband devices based on quantum wells and quantum dots, which could be used for infrared detection. A no-cost extension was requested for this project in October 2004 to extend the project to April 2005.

2.0 Relevance of Proposed Project

In the past few years, there has been active research on studying the performance characteristics of mid-wave infrared (MWIR, 3-5 μm) and long-wave infrared (LWIR, 8-12 μm) applications¹⁻¹⁰. MWIR and LWIR detectors are in great need for a variety of applications ranging from night vision cameras and battle recognition systems to chemical spectroscopy and remote sensing. Present day photon detectors in this wavelength range need to be cooled to liquid nitrogen temperature or below to reduce the deleterious effects arising from the large thermionic emission. Quantum dot detectors are expected to display low dark current¹¹, large detectivity¹² and better response at elevated temperature due to the longer lifetime of excited electrons due to greatly suppressed electron-phonon scattering^{13,14}. Quantum dot detectors have already demonstrated normal incidence MWIR operation at temperatures as high as 150K¹⁵ and the results reported in the literature from several groups show significant promise for this technology¹⁻¹⁰. Nevertheless the responsivity and specific detectivity of QDIPs is significantly lower than those observed in mercury cadmium telluride (MCT) detectors. However, due to difficulties with the epitaxial growth of mercury based compounds, material defects cause problems with uniformity and operability across an array that continue to plague MCT focal plane arrays. QDIPs, on the other hand, are based on a comparatively mature GaAs technology and the uniformity of their response suggests that they can be incorporated into large area focal plane arrays (FPA).

3.0 Summary of Technical Progress

The proposed project has yielded some remarkable breakthroughs not only in terms of the understanding of the fundamental science but also with respect to technological advances. This project has also led to a very close collaboration between UNM (Prof. Krishna's group) and AFRL/VSSS (Dr. Cardimona's group). Due to the success of this project, a spin-off company from UNM (Zia Laser Inc) has licensed the intellectual property and is covering the legal costs with the filing of the patent.

Some of the accomplishments of this project are:

- ***Use of a novel InAs/InGaAs quantum dots in a well (DWELL) heterostructure:***
The active region combines the advantages of conventional quantum well infrared photodetectors (QWIPs) and conventional quantum dot infrared photodetector (QDIPs). For example, it has a reproducible control over the operating wavelength

similar to a QWIP while having a response at normal incidence like a QDIP. Using this DWELL design, high performance detectors were designed, grown and characterized in the PI's group at UNM. Further detailed characterization was undertaken in collaboration with Dr. Cardimona's group.

- **First Report of Three Color Detector in the MWIR, LWIR and VLWIR:** Using a multi-stack InAs/InGaAs DWELL design, a multicolor detector spanning the MWIR (3-5 μm), LWIR (8-12 μm) and VLWIR ($\sim 25 \mu\text{m}$) regime was reported. We believe that the transitions are arising from different intersubband transitions in the DWELL heterostructure.
- **Theoretical Modeling of the DWELL Band structure:** Using two different approaches (finite element modeling and spectral based Jacobi-Tau decomposition), the complicated band structure of the DWELL detectors was modeled. The experimentally obtained photocurrent spectrum was in very good agreement with the theoretically calculated band structure.
- **Fabrication of the First Two Color Quantum Dot Camera:** In collaboration with Zia Laser Inc (a UNM based spin-off company) and BAE systems Inc, the PI's group reported the first two color QD camera. This camera was based on a 320x256 focal plane array and had response in the MWIR and LWIR bands.

4.0 Summary of Other Accomplishments

4.1 Dissemination of Knowledge

This project resulted in 22 conference proceedings, peer reviewed journals and articles, and 27 presentations (including multiple invited talks). One utility patent was also filed. The details are listed below:

4.1.1 Journals and Publications

- [1] S. Krishna, A. Stiff, P. Bhattacharya, and S. Kennerly " Hot Dot Detectors", *IEEE Circuits and Devices*, p.14, January 2002.
- [2] S. Krishna, S. Raghavan, A.L. Gray, A. Stintz and K.J. Malloy, "Characterization of Rapid-Thermal-Annealed InAs/In_{0.13}Ga_{0.87}As DWELL Dots using X-Ray Diffraction and Photoluminescence", *Appl. Phys. Lett.*, Vol. 80, 3898, 2002.
- [3] K. M. Lewis, Ç. Kurdak, S. Krishna and P. Bhattacharya, "Charge transformer to enhance noise performance of single-electron transistor amplifiers in high-capacitance applications", *Appl. Phys. Lett.*, **80**, 142, 2002.
- [4] S. Raghavan, P. Rotella, A. Stintz, B. Fuchs, S. Krishna, C. Morath, D. A. Cardimona, and S.W. Kennerly, "High-Responsivity, Normal-Incidence Long-Wave Infrared ($\lambda \sim 7.2 \mu\text{m}$) InAs/In_{0.15}Ga_{0.85}As Dots-in-a-Well Detector", *Appl. Phys. Lett.*, **81**, 1369, , 2002
- [5] X. Bai, Ç. Kurdak, S. Krishna, and P. Bhattacharya, "Quantum well based phonon detectors; performance analysis", *Physica B*, **316-317**, 362, 2002.

- [6] S. Krishna, A. Stiff, P. Bhattacharya, and S. Kennerly “ High Temperature operation of mid-infrared InAs/GaAs quantum-dot detectors”, *IEEE LEOS Newsletter*, January 2002.
- [7] C.P. Morath, D. Le, H.E. Norton, D.A. Cardimona, S. Ragahavan, P. Rotella, S. A. Stintz, B. Fuchs, S. Krishna “High responsivity, LWIR, dots-in-a-well quantum dot infrared photodetector” *Infra. Phys. & Tech*, **44**, 577 (2003).
- [8] S.Krishna, S. Raghavan, A. Stintz, C. Morath, H. Norton, D. Le, D. A. Cardimona, and S.W. Kennerly, “Radiometric Characterization of Normal-Incidence InAs/InGaAs Quantum-Dot Detectors” *Proc. SPIE*. **4823**, 75 (2002)
- [9] Hillary E. Norton, David A. Cardimona, Christian P. Morath, Dang T. Le, Dan Hong Huang, Sunil Raghavan, P. Rotella and Sanjay Krishna, “Transient effects in InAs/GaAs quantum-dot detectors under low-temperature and low-background conditions”, *Proc. SPIE*. **4823**, 104 (2002)
- [10] J. Sabarinathan, P. Bhattacharya, P-C. Yu, S. Krishna, J. Cheng, D. G. Steel, “An electrically injected InAs/GaAs quantum-dot photonic crystal microcavity light-emitting diode”, *Appl. Phys. Lett.*, **81**, 3876, , 2002
- [11] A. D. Stiff-Roberts, S. Krishna, P. Bhattacharya and S.W. Kennerly, “Low-bias, high-temperature performance of a normal-incidence InAs/GaAs vertical quantum-dot infrared photodetector with a current-blocking barrier”, *J. Vac. Sci. Tech. B*, **20**, 1185, 2002.
- [12] S. Raghavan, P. Rotella, A. Stintz, K.J. Malloy, S. Krishna, A.L Gray, “Structural and optical characterization of rapid thermally annealed InAs/In_{0.15}Ga_{0.85}As dots-in-well structure”, *J. Cryst. Growth*, **247**, 269-274, 2003.
- [13] P. Rotella, S. Raghavan, A. Stintz, B. Fuchs, S. Krishna, C. Morath, D. Le and S.W. Kennerly, “Normal incidence InAs/InGaAs dots-in-well detectors with current blocking AlGaAs layer”, *J. Cryst. Growth*, **251/1-4** pp. 787-793, 2003.
- [14] S. Krishna, S. Raghavan, G von Winckel, P. Rotella, A. Stintz, , C. Morath, D. A. Cardimona, and S.W. Kennerly, “Two Color InAs/InGaAs Dots-in-a-Well Detector with Background Limited Performance at 91K”, *Appl. Phys. Lett.*, **82**, 2574, 2003.
- [15] B. Kochman, A.D. Stiff-Roberts, S. Chakrabarti, J.D. Phillips, S. Krishna, J. Singh and P. Bhattacharya, “ Absorption, Carrier Lifetime, and Gain in InAs-GaAs Quantum Dot Infrared Photodetectors”, *IEEE. J. Quant. Electron.*, **39**, 459, 2003.
- [16] S. Krishna, S. Raghavan, G von Winckel, A. Stintz, , G. Ariyawansa, S.G. Matsik and A.G.U. Perera, “Three-Color ($\lambda_{p1} \sim 3.8 \mu\text{m}$, $\lambda_{p2} \sim 8.5 \mu\text{m}$ and $\lambda_{p3} \sim 23.2 \mu\text{m}$) InAs/ InGaAs Quantum Dots In a Well Detector”, *Appl. Phys. Lett.*, **83**, 2745, October 2003

- [17] U. Sakoglu, J. S. Tyo, M. M. Hayat, S. Raghavan, and S. Krishna, "Spectrally adaptive infrared photodetectors using bias-tunable quantum dots" *J. Opt. Soc. Am. B*, Vol 21, p.7, Jan 2004.
- [18] A. Amtout, S. Raghavan, P. Rotella, G. von Winckel, A. Stintz and S. Krishna "Theoretical Modeling And Experimental Characterization of InAs/InGaAs Quantum Dots In a Well Detector, *Journal of Applied Physics*, **96**, 3782, October 2004.
- [19] S. G. Matsik, M. B. M. Rinzan, D. G. Esaev, A. G. U. Perera, G. von Winckel, A. Stintz, and S. Krishna, H. C. Liu, M. D. Byloos, T. Oogarah, G. I. Sproule, K. Liu, and M. Buchanan, "Effect of doped substrate on IR detector response through cavity enhancement" (*Accepted in Applied Physics Letters*)
- [20] S. Raghavan, D. Forman, P. Hill, N. W- Bernstein, G. von Winckel, P. Rotella, S. Krishna, S. W. Kennerly and J. W. Little, "Normal-Incidence InAs/InGaAs Quantum Dots-in-a-Well Detector Operating in the Long Wave Infrared Atmospheric Window, *Journal of Applied Physics* **96**, 1036 (2004).
- [21] L.A. Farina, K.M. Lewis, C. Kurdak, S. Ghosh, S. Krishna and P. Bhattacharya, "Drag Coupling between a thin Al film and a two-dimensional electron gas near the superconducting transition", *Physica E* **22**, 341-344, 2004.
- [22] G. von Winckel, E. A. Coutias and S. Krishna, "Spectral Element Modeling of Semiconductor Heterostructure", Submitted to *Journal of Applied Physics*.

4.1.2 Conference Presentations

- [1] S. Krishna, A. Stiff, P. Bhattacharya, and S. Kennerly, "High Temperature Operation of Normally Incident Mid-Infrared ($\lambda=4\mu\text{m}$) InAs/GaAs Quantum-Dot Detectors" Rio Grande Regional Symposium on Advanced Materials, Albuquerque, NM, October 2001
- [2] A. Stiff, S. Krishna, P. Bhattacharya, and S. Kennerly, "High-temperature operation of mid-infrared ($\lambda=4\text{-}5\mu\text{m}$) vertical and lateral InAs/GaAs/AlGaAs quantum dot infrared photodetectors" Device Research Conference, South Bend, IN, June 2001.
- [3] S. Raghavan, A.L. Gray, A. Stintz, K.J. Malloy and S. Krishna, "Characterization of Rapid-Thermal-Annealed InAs/In_{0.13}Ga_{0.87}As DWELL Dots using X-Ray Diffraction and Photoluminescence", American Vacuum Society Meeting, Albuquerque, May 2002.
- [4] S. Raghavan, A.L. Gray, A. Stintz, K.J. Malloy and S. Krishna, "Structural and Optical Characterization of Rapid-Thermal-Annealed InAs/In_{0.13}Ga_{0.87}As DWELL Dots using X-Ray Diffraction and Photoluminescence" Electronic Materials Conference, Santa Barbara, CA, June 2002.

- [5] Sanjay Krishna, Sunil Raghavan, Christian Morath, Hillary Norton, Dang Le and David A. Cardimona, "Radiometric Characterization of Normally Incident Mid-Infrared InAs/GaAs Quantum-Dot Detectors", (INVITED) Photonics For Space Environments VIII, SPIE International Symposium on Optical Science and Technology, Seattle, WA, July 2002.
- [6] Sunil Raghavan, Sanjay Krishna, Beth Fuchs, Andreas Stintz, Kevin Malloy, Christian Morath, Dang Le and David A. Cardimona, "Normal Incidence Long-Wave Infrared InAs/In_{0.15}Ga_{0.85}As DWELL Detectors operating at 8.2 μ m", Device Research Conference, Santa Barbara, CA, June 2002.
- [7] Hillary Norton, Christian Morath, Dang Le, Danhong Huang, D. A. Cardimona, Sanjay Krishna and Sunil Raghavan, "Transient Effects in InAs/GaAs Quantum-Dot Detectors under Low Temperature and Low Background Conditions", (INVITED), Photonics For Space Environments VIII, SPIE International Symposium on Optical Science and Technology, Seattle, WA, July 2002.
- [8] S. Krishna, S. Raghavan, B. Fuchs, A. Stintz, K. Malloy, Christian Morath, Dang Le and S.W. Kennerly, "Normal Incidence, Long-Wave Infrared InAs/In_{0.15}Ga_{0.85}As Dots-in-Well Detectors Grown by Molecular Beam Epitaxy", International Molecular Beam Epitaxy Conference, San Francisco, CA, September 2002.
- [9] S. Krishna, "Performance of Long-Wave Infrared Dots-in-Well Detectors", Mid Infrared Optoelectronic Materials and Devices-V , Annapolis, DC, September 2002.
- [10] S. Krishna, P. Rotella, S. Raghavan, , A. Stintz, M. Hayat, S. J. Tyo and S.W. Kennerly, " Bias-Dependent Tunable Response of Normal Incidence Long Wave Infrared Quantum Dot Detectors" , IEEE/LEOS Annual Meeting, Glasgow, Scotland, November 2002.
- [11] G.V. Winckel and S. Krishna, "A Theoretical Model for Bias Dependent Shift of Absorption Spectra in Quantum Well Infrared Photodetectors" , IEEE/LEOS Annual Meeting, Glasgow, Scotland, November 2002
- [12] S.Krishna, "III-V based Mid Infrared Detectors", Bell Laboratories, December 2002 (INVITED TALK)
- [13] S. Krishna, S. Raghavan, G.V. Winckel, P. Rotella, A. Stintz, C. Morath, D. Le, S. W. Kennerly, " Two-Color Background Limited InAs/InGaAs Dots-in-a-Well Detectors", American Physical Society March meeting, Austin, TX, March 2003
- [14] Sunil Raghavan, Gregory von Winckel, Paul Rotella, Andreas Stintz and Sanjay Krishna, "Control of Operating Wavelength and Linewidth in LWIR InAs/InGaAs Dots-in-a-Well Detectors", *Device Research Conference*, Salt Lake City, UT, June 2003

- [15] S. Krishna, S. Raghavan, G von Winckel, A. Stintz, , G. Ariyawansa, S.G. Matsik and A.G.U. Perera, “Three-Color InAs/ InGaAs Quantum Dots In a Well Detector”, *International Symposium on Compound Semiconductors*, August 2003.
- [16] P. Rotella, G. von Winckel, S. Raghavan, A. Stintz and S. Krishna “Study of Optical Properties in Dots-in-a-Well Structure with varying Quantum Well Dimensions” North American Molecular Beam Epitaxy Conference, Keystone, CO, *October 2003*.
- [17] Sunil Raghavan, Darren Forman, Peter Hill, Gregory von Winckel, Andreas Stintz and Sanjay Krishna, “ Normal Incidence InAs/ InGaAs Quantum Dots-in-a-Well Photodetector spanning the 8-12 μm Atmospheric Window”, *Laser and Electro Optic Society Annual Meeting*, October 2003.
- [18] A. Amtout, S. Raghavan, P. Rotella , G. von Winckel, A. Stintz and S. Krishna “Theoretical Modeling and Experimental Characterization of InAs/InGaAs Quantum Dots In a Well Detector” *Laser and Electro Optic Society Annual Meeting*, October 2003.
- [19] S. Krishna, S. Raghavan, G. von Winckel, A. Stintz, R. P. Prasankumar, R. D. Averitt, A. J. Taylor (LANL), “Quantum Dots-in-a-Well Detectors: Carrier Dynamics and Performance Characteristics”, *American Physical Society meeting*, Montreal, TX, March 2004
- [20] (INVITED) S. Krishna, “Quantum Dots-in-a-Well Infrared Photodetectors for MWIR, LWIR and VLWIR Applications”, *International Symposium on Physics of Semiconductors and Applications*, Gyeongju, Korea, March 2004
- [21] “Time-resolved mid-infrared dynamics of an InAs/InGaAs quantum-dots-in-a-well detector”, R. P. Prasankumar, R. D. Averitt, A. J. Taylor (LANL), G. von Winckel, A. Stintz and S. Krishna (UNM), *Conference on Laser/Electro-optics*, San Francisco May 2004
- [22] “Investigation of the energy-dependent charge dynamics in InAs SAQD’s with Ultrafast Scanning Tunneling Microscopy.”, D. Yarotski, A. J. Taylor (LANL), A.L. Gray and S. Krishna (UNM), *Conference on Laser/Electro-optics*, San Francisco May 2004
- [23] (INVITED) Sanjay Krishna, Sunil Raghavan, Greg von Winckel, Andreas Stintz, G. Ariyawansa, S.G. Matsik and A.G.U. Perera “ Three color Quantum Dots in a Well Detector”, SPIE conference on Infrared Spaceborne Remote Sensing, Aug 2004
- [24] Z. Wang, U. Sakoglu, S. Raghavan, J. S. Tyo, M. M. Hayat, and S. Krishna, “Real Time implementation of matched filtering algorithms using adaptive focal plane array technology” *SPIE Imaging Spectrometry Meeting*, 2004.

- [25](INVITED) Sanjay Krishna, “ Multicolor Quantum Dot Detectors”, 206th Electrochemical Society Annual Meeting, Honolulu, October 2004.
- [26]Sanjay Krishna, “Spectrally Adaptive Nanoscale Quantum Dot Sensors”, Technical Seminar, National Reconnaissance Organization, October 2004.
- [27]G. von Winckel, E. Coutias and S. Krishna, “The Helmholtz Eigenproblem in Elliptical Domains using Spectral Tau-Method and Conformal Mapping”, International Conference on Spectral and High Order Methods, Providence, RI June 2004.

4.1.2 Book Chapters and Patents

In addition to this, the PI wrote two book chapters on the self assembled QD detectors. One utility patent was filed as a result of work from this project and a company has negotiated the licensing of this technology from the University of New Mexico.

1. S.Krishna, “Optoelectronic Properties of Self Assembled InAs/InGaAs Quantum Dots” in III-V Compound Semiconductor Heterojunctions: Physics And Devices, Publisher, Transworld Research, ISBN 81-7736-170-8, Editor: Will Z. Cai, 2003.
2. P. Bhattacharya, S. Krishna, A. D. Stiff, “ Quantum Dot Infrared Detectors and Sources”, Int. Journal of High Speed Electronics and Systems, vol. 12, No. 4, pp. 969-994, 2002 (World Scientific Publishing Company)

Patent: S. Krishna, M. Hayat, J. S. Tyo, U. Sakoglu and S. Raghavan “Spectrally Adaptive Quantum Dots In A Well Detector”, Utility Patent Filed (# 68986), September 2004.

4.2 Training of DOD Personnel

The PI’s group works very closely with Dr. Cardimona’s group at AFRL/VSSS. As a result of this close interaction, there is a lot of exchange of scientific information between the PI’s group and Dr. Cardimona’s group. Three DOD personnel, Capt. Mario Serna, Capt. Christian Morath and Capt. Dang Le worked very closely with the PI. Capt. Mario Serna received his M.S. by thesis under the supervision of the PI and is presently teaching at the Air Force Academy in Colorado Springs. Capt. Serna was also a finalist in the prestigious Hewlett Packard intercollegiate inventors competition under the supervision of the PI. Capt. Morath is presently undertaking research at Hanscom Air Force Base and hopes to return this year to resume his PhD at the University of New Mexico. Capt. Le continues to work closely with the PI as he characterizes the infrared detectors grown in the PI’s group.

5.0 Detailed Progress

5.1 Growth of InAs/InGaAs quantum dots in a well detectors: InAs/InGaAs quantum dots in a well (QDWELL) detectors were designed, grown, fabricated and characterized in the PI's group. Transmission electron microscopy images revealed that there were no defects in the device ensuring the good optical quality of the sample. Using standard cleanroom lithography techniques, such as wet and dry etching, metal evaporation and annealing, n-i-n detectors were fabricated. Devices with different active area dimensions were fabricated. The diameter of the devices varied from 25 μm to 300 μm . The devices were then wire bonded on to a chip carrier and delivered to Dr. Dave Cardimona's group at the Air Force Research Laboratory. Extensive blackbody and noise characterization was performed on these detectors. A picture of the actual device and the heterostructure is shown in Fig. 1.

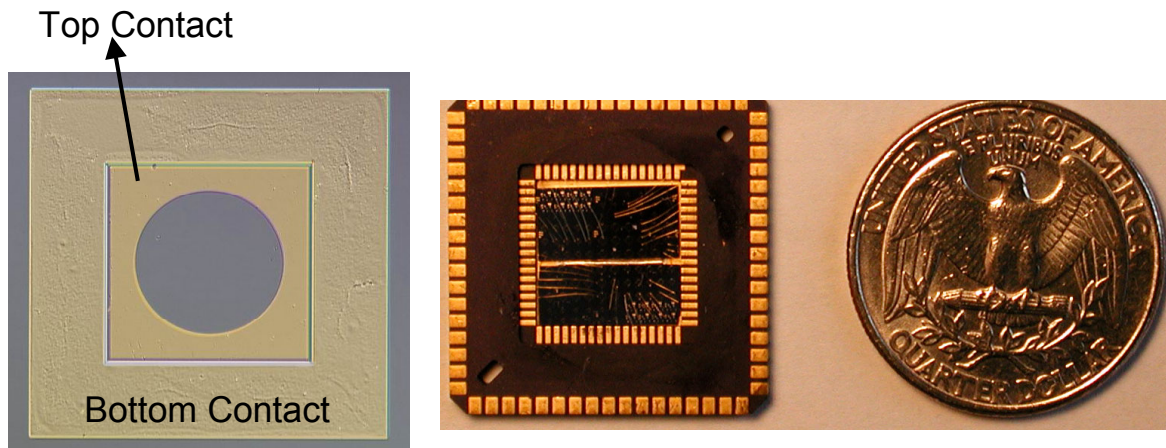


Fig. 1: (a) Image of a processed n-i-n quantum dot infrared detector (b) mounted on a leadless chip carrier for delivery to Dr. Cardimona's group at AFRL/VSSS

Preliminary characterization revealed that the detectors display a broad band response close to 8 μm . This is ideal for application to the long-wave infrared (LWIR) window of the atmospheric transmission. Some of the preliminary characteristics of the detectors are shown in Fig. 2. Further radiometric characterization of the detectors has been undertaken at the Air Force Research Laboratory.

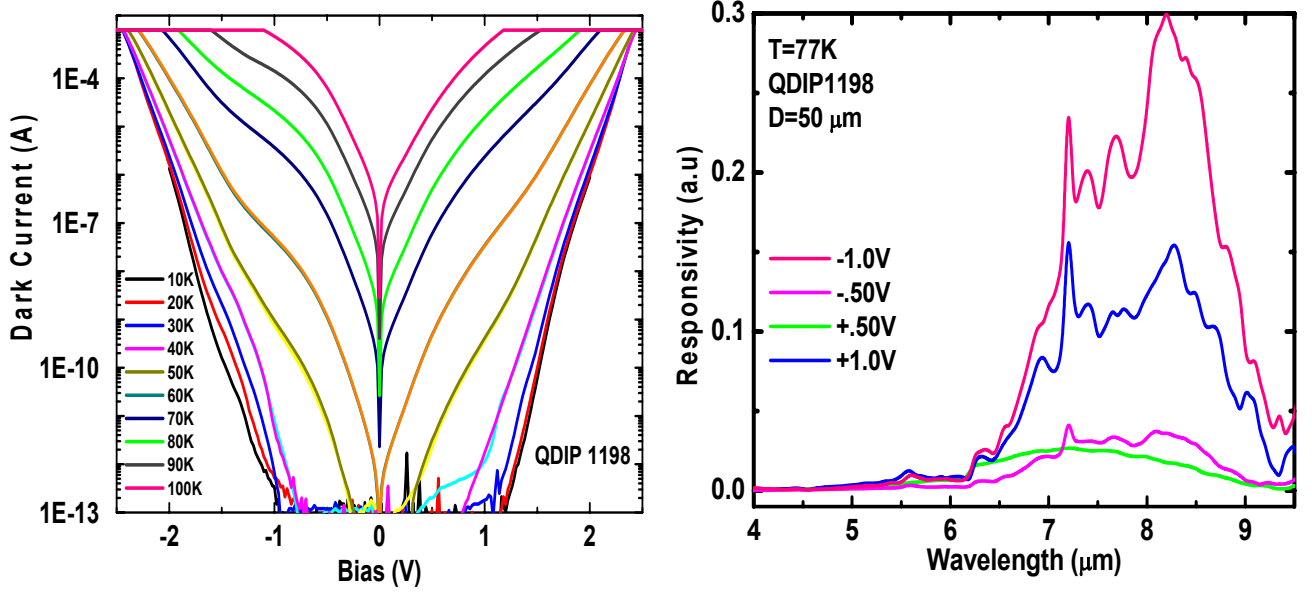


Fig 2: Dark current and spectral response of a 10 layer InAs/InGaAs a quantum dot infrared detector. The measurements were performed by Dr. Cardimona's research group at the Air Force Research Laboratory.

The operating wavelength of the detector was controlled by varying the width of the InGaAs well.

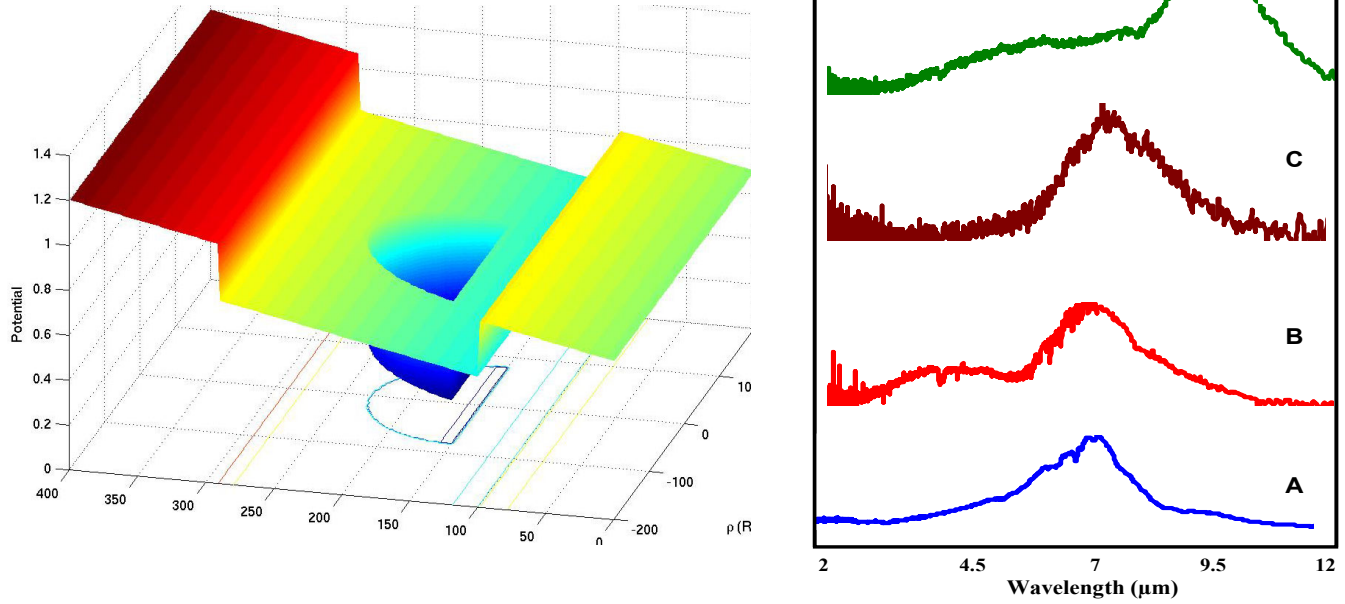


Fig. 3: (a) Potential profile in a typical dots in a well structure and (b) normalized photoresponse per watt for DWELL sensors with different well widths. The wavelength shifts progressively from 7.3 μm to 9.7 μm .

Two novel InAs/InGaAs quantum dots in well (DWELL) detectors were designed, grown, fabricated and characterized. One of them was a spectrally adaptive design with tunable operation expected between 5-8 μm (Sample #1517), whereas the other was a long wave infrared design (Sample #1517). Photoluminescence spectral maps were obtained from these samples to estimate the uniformity of the quantum dots over a 2" wafer. Figure. 4 summarizes the results of the measurements. Extremely uniform response was obtained from both these wafers as summarized below.

"Spectrally Adaptive" DWELL

$\lambda_p(\text{design}) \sim 7 \mu\text{m}$ at -1V

PL Peak = 1220.7 nm

σ (PL peak) = 2.5nm (0.21%)

"Atmospheric Window" DWELL

$\lambda_p(\text{design}) \sim 10 \mu\text{m}$ at -2V

PL Peak = 1212.0 nm

σ (PL peak) = 5.6 nm (0.45%)

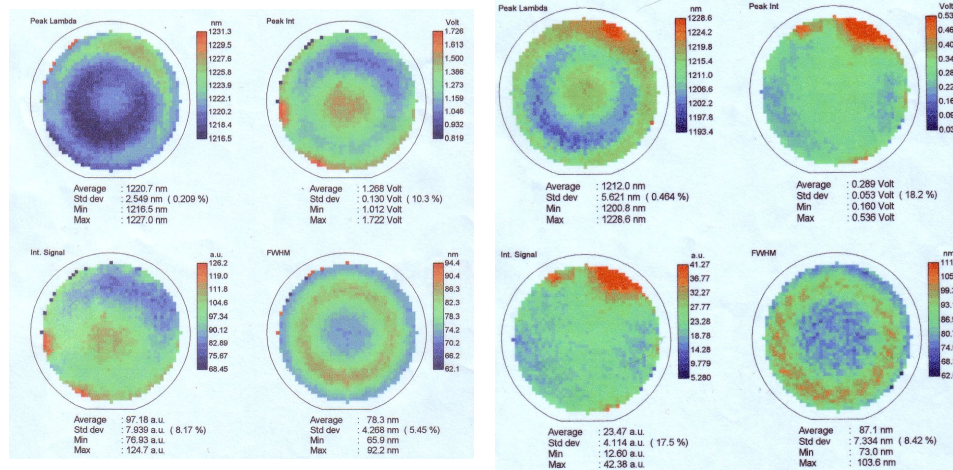
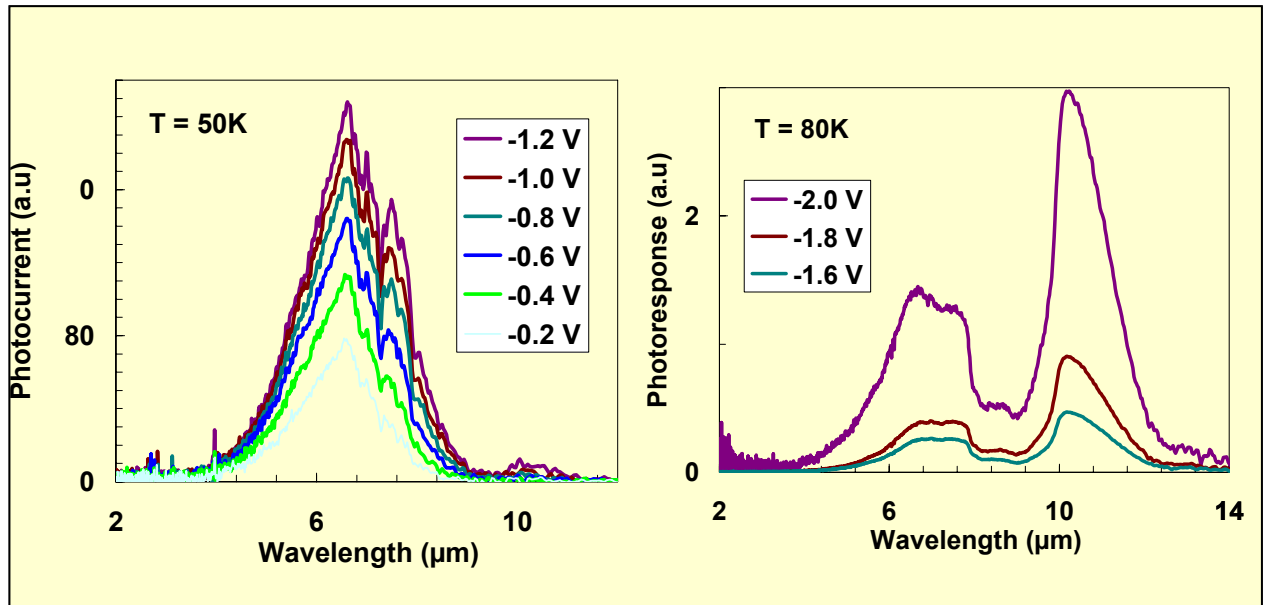


Fig. 4: PL spectra maps of DWELL detector with two different designs. One with a spectrally adaptive design and the other with an optimized LWIR response. The photocurrent spectra from these detectors is shown below.

Spectral measurements for these detectors were undertaken in Prof. Krishna's group at CHTM. The figure below shows the intersubband photocurrent obtained from these two detectors.



A three color quantum dot detector operating in the MWIR (3.8 μm), LWIR (8.5 μm) and VLWIR (23.2 μm) was also designed grown and fabricated in the PI's lab, as shown below.

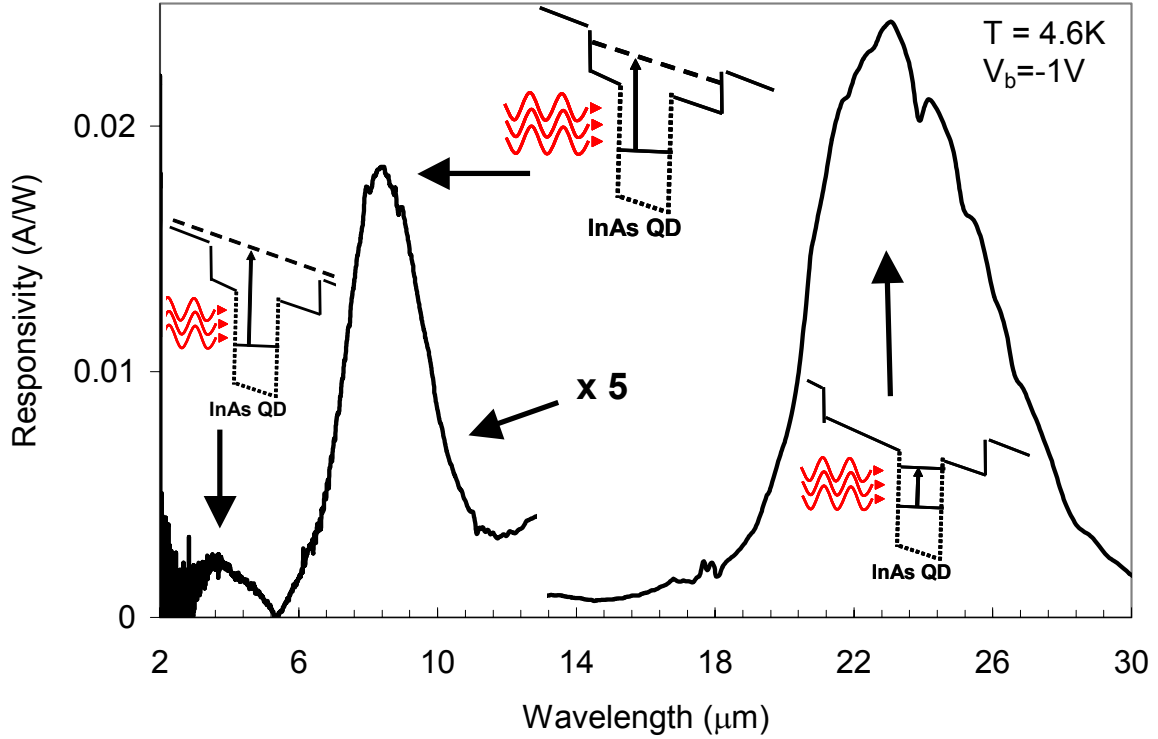


Fig. 5: Three color response from Quantum Dots in a Well detector. The inset shows the participating intersubband transitions.

Theoretical modeling and experimental characterization of InGaAs/GaAs quantum dots-in-a-well (DWELL) intersubband heterostructures, grown by molecular beam epitaxy (MBE) were undertaken. In this heterostructure, the self-assembled dots are confined to the top half of a 110 Å InGaAs well which in turn is placed in a GaAs matrix. Using transmission electron microscopy (TEM), the quantum dots are found to be pyramidal in shape with a base dimension of 110 Å and height of 65 Å. The band structure for the above mentioned DWELL heterostructure was theoretically modeled using a Bessel function expansion of the wavefunction (Fig. 6). The energy levels of the three lowest states of the conduction band of the quantum dot are calculated as a function of the electric field. Intersubband n-i-n detectors were fabricated using a 10 layer DWELL heterostructure. The spectral response of the detector is measured at a temperature between 30-50K and compared with the prediction of our theoretical model.

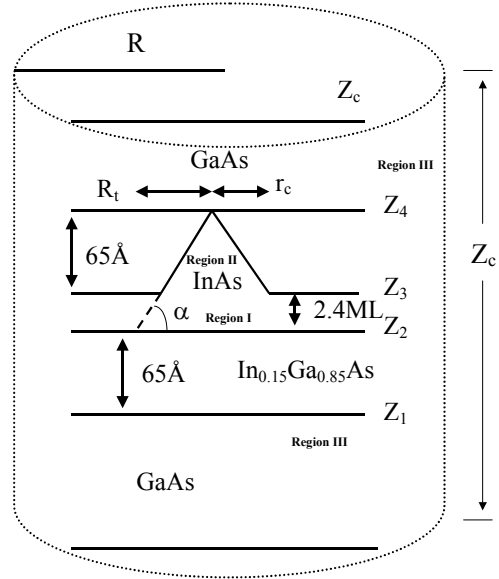
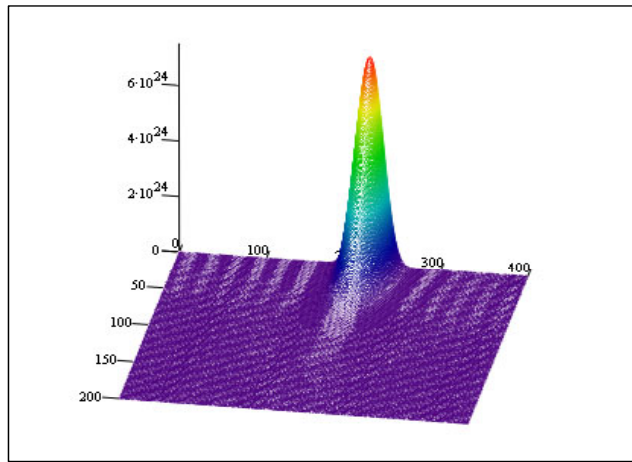
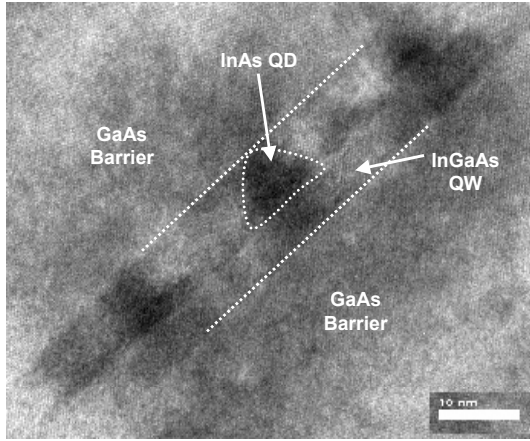


Fig. 6: (a) Transmission electron microscopy of the DWELL structure, (b) the theoretical model that was used to define the electronic potential, (c) the ground state wavefunction in the DWELL system.

5.2 Fabrication of the First Two Color Quantum Dot Camera: In collaboration with Zia Laser Inc (a UNM based spin-off company) and BAE systems Inc, the PI's group reported the first two color QD camera. This camera was based on a 320x256 focal plane array and had response in the MWIR (3-5 μm) and LWIR (8-12 μm) bands. This was used to obtain images in the MWIR and LWIR as shown in Fig. 7.

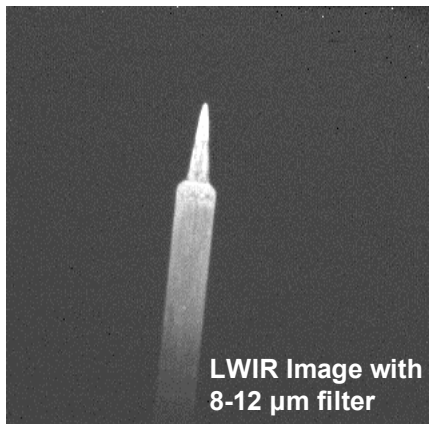


Fig. 7: Images from the first LWIR quantum dot based camera. Image of (a) soldering iron at $\sim 600\text{K}$ and (b) a scientific personnel at 300K using a 320 x256 focal plane array. This was a result of a collaboration between the PI's group, Zia Laser Inc and BAE systems Inc.

6.0 Conclusions and Future Work

As mentioned above, this project has significantly impacted the research of intersubband devices based on quantum wells and quantum dots. This project encompassed the theoretical modeling of intersubband detectors, their design, growth, fabrication and characterization. This has led to a number of peer-reviewed publications, conference presentations and the filing of a utility patent. The PI wishes to continue this work by evaluating the performance of these detectors along with respect to another emerging technology, namely the strain layer superlattice detectors. The PI has submitted a proposal to AFRL/VSSS on this topic and is waiting to hear the outcome of the evaluation process.

7.0 References:

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1. K. W. Berryman, S. A. Lyon and M. Segev, *Appl. Phys. Lett.* **70**, p.1861, 1997.
2. J. Phillips, P. Bhattacharya, S. W. Kennerly, D. W. Beekman, and M. Dutta, *IEEE J. Quant. Electron.*, **35**, p. 936, 1999.
3. S. Maimon, E. Finkman, G. Bahir, S.E. Schacham, J.M. Garcia and P.M. Petroff, *Appl. Phys. Lett.*, **73**, p. 2003, 1998.
4. D. Pan, E. Towe, and S. Kennerly, *Appl. Phys. Lett.*, **73**, p. 1937, 1998.
5. H. C. Liu, M. Gao, J. McCaffrey, Z. R. Wasilewski, and S. Fafard, *Appl. Phys. Lett.*, **78**, 79 (2001).
6. S. Kim, H. Mohseni, M. Erdtmann, M. Michel, J. Jelen, and M. Razeghi, *Appl. Phys. Lett.*, **73**, 963 (1998).
7. L. Chu, A. Zrenner, G. Bohm, and G. Abstreiter, *Appl. Phys. Lett.*, **75**, 3599 (1999).
8. S-W. Lee, K. Hirakawa and Y. Shimada, *Appl. Phys. Lett.*, **75**, 1428 (1999).
9. N. Rappaport, E. Finkman, T. Brunhes, P. Boucaud, S. Sauvage, N. Yam, V. Le Thanh, and D. Boucher, *Appl. Phys. Lett.*, **77**, 3224 (2000).
10. Z. Chen, O. Baklenov, E.T. Kim, I. Mukhametzhanov, J. Tie and A. Madhukar, *J. Appl. Phys.*, **89**, 4558 (2001).
11. V. Ryzhii, I. Khmyrova, V. Mitin, M. Strosio, M. Willander, *Appl. Phys. Lett.*, **78**, 3523 (2001).
12. J. D. Phillips, *J. Appl. Phys.*, **91**, 4590 (2002).
13. U. Bockelman and G. Bastard, *Phys. Rev. B*, **B42**, 8947, (1990).
14. H. Benisty, C. M. Sotomayer-Torres, and C. Weisbuch, *Phys. Rev. B*, **B44**, 10945, (1991).
15. A. D. Stiff, S.Krishna, P. Bhattacharya, and S. Kennerly, *Appl. Phys. Lett.*, **79**, 421 (2001).

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